Lateral Meniscus Tear Propagation and Effect on Knee Kinematics

ABSTRACT

Background: It is unknown if certain activities performed in sports practice have implications on the size of meniscal tears left in situ when performed. The purpose of this study was to quantify propagation of small longitudinal tears in the lateral meniscus and the resulting changes in knee kinematics and kinetics.

Methods: Using a robotic testing system, 5-N•m of external tibial torque + 5-N•m of valgus torque + 250-N of axial compression was applied to 14 fresh-frozen cadaveric knees while the knees were flexed from 30° to 90° of flexion. The knees were divided into two groups - ACL-Intact (N=8) and ACL-Deficient (N=6). Data was recorded for four knee states: starting knee state, after posterior arthrotomy, meniscus tear at baseline, and after 500 cycles of the applied loading condition. For statistical analysis, an analysis of variance was used; significance was set at $P < .05$.

Results: Lateral meniscus tear length increased significantly throughout the 500 cycles regardless of the ACL integrity ($p < 0.05$). Overall, an increase of 28.7% and 26.1% was observed in intact and ACL deficient knees, respectively. In intact knees, external tibial rotation increased with meniscus tear propagation at all flexion angles by up to 45.5% ($p < 0.05$). In contrast, tibiofemoral kinematics in ACL deficient knees were not significantly affected by meniscus tear propagation (NS). The only significant differences following tear propagation were the resultant forces in the lateral meniscus in ACL deficient knees at all flexion angles ($p < 0.05$) and bony contact forces at the tibiofemoral joint in intact knees at 60° of flexion ($p < 0.05$).

Conclusions: Small longitudinal lateral meniscus tears propagate significantly regardless of ACL integrity and after only 100 cycles of simulated cyclic cutting maneuvers. The propagation of such tears altered kinematics and forces in the knee.

Clinical Relevance: Small, vertical longitudinal lateral meniscus tears that are left in situ in current clinical practices may propagate when loaded, leading to changes in knee kinematics and forces.
INTRODUCTION

It has been well described in the literature a number of factors related to a better healing prognosis of meniscal injuries: (1) peripheral tears[1, 2], (2) vertical longitudinal tears[3], (3) younger age[4], (4) acute tears[5], (5) smaller tears[5], (6) concomitant anterior cruciate ligament (ACL) reconstruction[5-7] and (7) lateral meniscus[8, 9]. Taking into consideration these factors, it has been suggested that peripheral, longitudinal tears measuring <10 mm in length may be left untreated (i.e., in situ) at the time of ACL reconstruction with low reoperation rate and considerable success in long-term subjective and objective criteria[9-13]. Additionally, a study has shown that for the lateral meniscus, meniscal tears left in situ, irrespective of its size, had no clinical impact at 4 years of follow-up[14]. However, considering the significant load distribution and stability functions of the meniscus, it is unknown if load bearing activities such as cutting maneuvers have implications on tear length of meniscal tears left in situ. Thus, whether specific activities can increase meniscal tear length after time and thus lead to unstable and symptomatic lesions, which may have lower healing capacity or repair feasibility when addressed after tear propagation compared to the acute setting, is critical to understand. Furthermore, since concomitant meniscal and ACL injuries are frequently seen[15, 16], the consequences of meniscal tears in both intact and ACL-deficient knees are of interest. Therefore, the objectives of this study were to quantify propagation of small vertical longitudinal tears in the posterior horn of the lateral meniscus during simulated cyclic cutting maneuvers on a robotic testing system, the resulting changes in knee kinematics, resultant forces in the lateral meniscus, in situ force in the ACL, and tibiofemoral bony contact forces. Because of knee loading during weight bearing activities, it was hypothesized that small vertical longitudinal tears in the posterior horn of the lateral meniscus would increase in length after cyclic loading, and, consequently, an increase in kinematics would occur in intact and ACL-deficient knees. It was also hypothesized that propagation of the meniscal tear would cause a decrease in the resultant forces in the lateral meniscus and an increase in the in situ force in the ACL and in the tibiofemoral bony contact forces.

MATERIALS AND METHODS

Fourteen fresh-frozen cadaveric knees (mean age 74.8; range 51-92 years) were used in this study. Each specimen was carefully examined manually, radiographically, and arthroscopically before testing to exclude specimens with (1) bony deformities, (2) ligamentous injuries, (3) meniscal injuries, (4) osteoarthritis greater than grade 2 as determined by the Kellgren-Lawrence grading scale[17] or (5) chondral injuries greater than
grade 2 according to the International Cartilage Repair Society grading system[18]. The knee was mounted onto a 6-degree-of-freedom (6-DOF) robotic testing system (MJT model FRS2010; Technology Service, Chino, Japan) with a universal force/moment sensor (UFS; Delta IP60 [SI-660-60]; ATI Industrial Automation).

The specimens were divided in two groups, intact (N=8) and ACL-Deficient (N=6). One loading condition consisting of 5-N•m of external tibial torque + 5-N•m of valgus torque + 250-N of axial compression was applied to both groups while the knees were continuously flexed from 30º to 90º of knee flexion. After recording the knee kinematics in response to loading of intact knee, in the ACL-deficient group knees, the ACL was resected arthroscopically at this point and the knee tested. Then, a 3 cm posterior incision and arthrotomy were made and, after access to the posterior horn of the lateral meniscus was accomplished, the capsule and the skin were closed in a standardized fashion and the knee tested. This step was performed to evaluate whether the posterior approach to the lateral meniscus would interfere in the knee kinematics and forces. Next, the incisions were open and a small vertical longitudinal tear in the posterior horn of the lateral meniscus, posterior to the popliteus tendon, was created in the periphery region with a scalpel blade (Figure 1). The length of the tear created was measured with a custom-made device (Figures 1C and 2 - accuracy 0.2 mm, inter-rater reliability 0.914). The knee was once again tested with the same loading condition for 500 cycles, with the meniscal tear length being measured after each 100 cycles as described. After each measurement, the posterior capsule and skin were closed in a standardized fashion.

![Figure 1: Creation of the meniscal vertical longitudinal tear. (A) Posterior view of the knee; (B) *Schematic representation of the tear created (C) Custom-made measurement device in use.](image)

Further, in the intact knees, the ACL was resected arthroscopically at this point and previous positions of the knee were repeated, in order to quantify the in situ force in the ACL using the principle of superposition[19-21]. Next, the lateral meniscus was removed through
the posterior approach and previous positions were again repeated, in order to quantify the resultant forces in the lateral meniscus (i.e., the forces the meniscus carries in response to a given load applied to the knee[22]) also using the principle of superposition. Lastly, the tibiofemoral bony contact forces were also quantified using the principle of superposition by repeating recorded paths after removal of all soft-tissue. The 6-DOF kinematics data was recorded for all four knee states: (1) starting knee state (either intact or ACL-deficient), (2) after posterior arthrotomy, (3) meniscus tear at baseline and (4) after 500 cycles of the applied loading condition.

For statistical analysis, a repeated-measures analysis of variance (ANOVA) with a post-hoc Bonferroni correction was used to analyze meniscus tear propagation, knee kinematics, and resultant forces at 30°, 60° and 90° of knee flexion between the knee states. All statistical analyses were performed using SPSS software (version 24 for Mac; SPSS Chicago, IL). Significance was set at $P < .05$.

**Figure 2**: Custom-made measurement device. (A) tip height: 5 mm; (B) tip width: 10 mm

**RESULTS**

**Lateral meniscus tear propagation**

In the intact knees, the small vertical lateral meniscus tear propagated significantly from baseline (11.5mm ± 0.9mm) by 1.6mm at 100 cycles ($p < 0.001$), 2.1mm at 200 cycles ($p < 0.001$), 2.4mm at 300 cycles ($p < 0.001$), 2.8mm at 400 cycles ($p < 0.001$) and 3.3mm at 500 cycles ($p < 0.001$). This corresponds to an overall tear propagation of 28.7 ± 5.4% (Figure 3, 4).

In the ACL deficient knees, the meniscus tear length increased from 12.1mm ± 1.6mm at baseline by 1mm at 100 cycles ($p = 0.001$), 2.2 at 200 cycles ($p = 0.001$), 2.5mm at 300 cycles ($p < 0.001$), 2.8mm at 400 cycles ($p < 0.001$) and 3.1mm at 500 cycles ($p < 0.001$). This corresponds to a tear propagation of 26.1 ± 8.3%. No significant differences were observed between intact and ACL deficient knees (NS) (Figure 4).
Figure 3: Lateral meniscus with propagated tear in the posterior horn after robotic testing. *After propagation, the tear had irregular and friable edges, instead of the blunt cut initially made with the scalpel blade.

Tear size (mm)

![Bar chart showing tear size over cycles](image)

Figure 4: Lateral meniscus tear propagation from baseline (cycle 0) to 500 cycles with 5-N•m of external tibial torque + 5-N•m of valgus torque + 250-N of axial compression between 30° and 90° of flexion. Overall, a significant increase in meniscus tear propagation was observed for both intact knees and ACL deficient knees. * indicates a significant difference from the tear at baseline (p< 0.05); ** indicates a significant difference to the previous cycle number (p < 0.05).

Tibiofemoral kinematics
In intact knees external tibial rotation increased with lateral meniscus tear propagation from 16.3° (± 3.5°) to 22.5° (± 8.8°) at 30° of flexion (p = 0.024), from 18.1° (± 4.4°) to 25.7° (± 9.7°) at 60° of flexion (p = 0.014), and from 17.6° (± 3.8°) to 25.6° (± 9.6°) at 90° of flexion (p = 0.019). This corresponds to an increase of external tibial rotation of 38.0%, 42.0% and 45.5% at 30°, 60° and 90°, respectively (Figure 5A). Furthermore, intact knees displayed significantly more valgus at 30° after meniscus tear propagation (p < 0.05), while anterior tibial translation was not significantly affected by lateral meniscus tear propagation (NS).

In ACL deficient knees, lateral meniscus tear propagation did not significantly affect knee kinematics (NS; Figure 5B).

No significant differences were observed between intact and ACL deficient knees (NS).
**Figure 5 A, B:** With lateral meniscus tear, external tibial rotation increased significantly from baseline to 500 cycles in intact knees (p < 0.05). Despite an increased external tibial rotation in ACL deficient knees, no statistically significant difference was observed. No significant differences were observed between intact and ACL deficient knees (NS). * indicates a significant difference from the tear at baseline (p<0.05).

*Resultant forces*

The in situ force in the ACL increased from baseline to cycle 500 from 79.5 N ± 51.7 N by 55.7% to 104.0 N ± 85.6 N at 30°. However, no statistically significant change was observed (NS). The resultant force in the lateral meniscus increased with lateral meniscus tear propagation in the intact knees from 62.3 N (± 41.4 N) by 36.1% to 84.8 N (± 57.3 N), from 49.5 N (± 50.0 N) by 54.1% to 76.3 N (± 53.8 N), and from 50.1 N (± 44.8 N) by 32.3% to 66.3 N (± 54.7 N)) at 30°, 60°, and 90°, respectively (NS). Similarly, the resultant force in the lateral meniscus increased in the ACL deficient knees from 49.8 N (± 28.4 N) by 116.5% to 107.8 N (± 61.8 N) (p = 0.012), from 65.1 N (± 60.0 N) by 81.4% to 118.1 N (± 70.7 N) (p = 0.012), and from 60.6 N (± 72.5 N) by 53.8% to 93.2 N (± 84.0 N) (p = 0.035) at 30°, 60° and 90° of flexion (Figure 6 A,B).
Figure 6 A, B: The resultant force in the lateral meniscus increased with lateral meniscus tear propagation by up to 116.5%. However, a significant increase was only observed in ACL deficient knees at 30°, 60°, and 90° of knee flexion (p < 0.05). No statistically significant differences were observed between intact and ACL deficient knees (NS). * indicates a significant difference from the tear at baseline (p< 0.05).

In intact knees, bony contact forces at the tibiofemoral joint increased from the tear at baseline to cycle 500 from 133.9 N (± 111.6 N) by 91.9% to 256.9 N (± 86.1 N) (NS), from 142.3 N (± 71.8 N) by 69.6% to 241.3 N (± 60.2 N) (p = 0.017) and from 174.9 N (± 78.9 N) by 37.6% to 240.6 N (± 60.5 N) (NS) at 30°, 60° and 90° of knee flexion (Figure 7A). Similarly, in ACL
deficient knees, bony contact forces at the tibiofemoral joint were not significantly affected by lateral meniscus tear propagation (NS; figure 7B). Bony contact forces at the tibiofemoral joint were statistically significant higher in ACL deficient knees compared to intact knees following meniscus tear propagation (p < 0.05) at 30° of knee flexion.

Figure 7 A, B: Bony contact forces at the tibiofemoral joint in intact (black bars) and ACL deficient knees (grey bars). A significant increase between the bony contact forces at the tibiofemoral joint at baseline and following tear propagation was observed in intact knees at 60° of knee flexion (p < 0.05). At 30° of knee flexion, bony contact forces at the tibiofemoral joint were significantly different between intact and ACL deficient knees at 30° of knee flexion (p < 0.05). * indicates a significant difference from the tear at baseline (p< 0.05); ** indicates a significant difference between intact and ACL deficient knees (p < 0.05).

DISCUSSION
The main finding of this study was that small vertical longitudinal tears in the posterior horn of lateral meniscus significantly propagated after simulated cyclic cutting maneuvers in intact and ACL-deficient knees. Furthermore, propagation of meniscal tears increased external rotation of the tibia and tibiofemoral bony contact forces in the intact group, while increased resultant forces in the lateral meniscus in the ACL-deficient group.

Meniscal tear propagation of small lateral meniscus tears observed in the current robotic study are in contrast to previous clinical studies which reported that small, vertical and stable tears in the posterior horn of the lateral meniscus could be left in situ. A previous study analyzed 208 meniscus tears left in situ at the time of ACL reconstruction, with a minimum 6-year follow-up, and reported that 91.8% of patients did not require reoperation for meniscus lesions[11]. However, no clinical information was provided, thus whether these patients did not return to their pre-operative activity level that could lead to propagation of the meniscal tears, and how many symptomatic patients did not undergo reoperation, which could underestimate the failure rate of this treatment option, is unknown. Additionally, the current study observed that external rotation and bony contact forces are significantly altered if a meniscal tear is left in situ, likely adding to poor outcome. Another study evaluated 332 patients who underwent ACL reconstruction with lateral meniscus tears that were left in situ or that underwent abrasion and trephination at a mean of 6.6 years after surgery[10]. The authors reported the lowest re-tear rate in patients with peripheral or posterior tears (1.8%) and highest with radial flap tears (6%). Still, re-tear rate was also obtained considering only subsequent surgery and abrasion and trephination were used in a number of tears which may increase their ability to heal, although no significant difference in the subjective and objective scores of those with peripheral or posterior tears treated by abrasion and trephination from those that were left in situ were observed. Additionally, objective and subjective criteria were applied for several patients with satisfactory results.

A study that investigated the healing potential of meniscal tears left in situ during ACL reconstructions and performed second-look arthroscopy in all cases observed that only 56% of the medial meniscus tears and 74% of the lateral meniscus tears were completely healed[9]. Noteworthy, 10% of the medial meniscus tears and 7% of the lateral meniscus tears were reported as expanded lesions compared to the original tear left in situ, and a number of patients with menisci evaluated as expanded had clinical symptoms of locking and catching. The reported propagation of meniscal tears observed in the second-look arthroscopies agrees with the results of tear propagation observed in the present study, in which a simulated cutting maneuver was performed by the robotic testing to evaluate if, when subjected to such maneuvers, the small and stable meniscal tears would propagate. It was observed that about 25% of the meniscal tears propagated, regardless of the integrity of the ACL. These
propagated tears may have inferior prognosis to repair if they propagate into complex tears, propagate to the inner region of the meniscus, or are chronically addressed. The propagation of meniscal tears in the present study increased external rotation of the tibia in the intact group, which can be related to previous studies. Since one of the main functions of the meniscus is to provide joint stability\[23, 24\], and the lateral meniscus in particular has been shown to play a role in conferring rotatory instability to the knee\[25\], the increase in external rotation after tear propagation reported in the present study suggests that it may lead to rotatory instability of the knee. Additionally, the increase in resultant forces in the lateral meniscus in the ACL-deficient group observed in this study correlates to previous literature, whereas several studies have shown an increased failure rate of meniscal repairs in ACL-deficient knees\[26-28\]. Thus, the increased forces in the lateral meniscus could explain the inferior results previously reported after meniscal repairs in ACL-deficient knees due to an overload of the meniscus, which may jeopardize the repair and predispose to further injuries. Furthermore, tibiofemoral bony contact forces increased in the intact group after meniscal tear propagation. This could have negative long-term effects on the tibiofemoral cartilage, as it can be correlated to the increase in peak tibiofemoral contact pressure observed after lateral meniscectomy and to the increase in the incidence of OA after these procedures\[29-32\].

Altogether, based on the data of this robotic study, even small, stable vertical longitudinal tears in the lateral meniscus might be clinically relevant, as their propagation can lead to changes in knee kinematics and forces, and be related to the results of the above-cited study that reported clinical symptoms in patients with propagated meniscal tears\[9\]. Thus, the authors of the present study recommend that such tears should be carefully followed in patients. Future research will focus on strategies to prevent tear propagation and evaluate if repair of these tears may prevent tear propagation and its consequences in response to the same loading conditions.

A limitation of the study is that the performance of a number of posterior arthrotomies after every 100 cycles of the applied loading condition to measure the tear length could lead to kinematic changes by itself since the capsule plays a role in knee stability. However, we tested the knees after only creating and suturing the posterior arthrotomy and no significant differences compared to the starting knee state were observed. The propagation of meniscal tears in the robotic testing may not reflect the tear propagation in vivo, in which the meniscus may have time and vascularization to heal after being subjected to loads such as the simulated one in this study. The age of specimens used in this study is older than the population of patients that usually sustain such small stable tears that are considered for repair. Additionally, the older specimen age may also be relevant to tissue properties being different compared to younger specimens.
CONCLUSION

The data of this study suggests that small vertical longitudinal lateral meniscus tears propagate significantly regardless of the integrity of the ACL and even after only 100 cycles of knee loading. The propagation of such tears altered kinematics and forces in the knee, with an increase in external rotation of the tibia, forces in the lateral meniscus, and tibiofemoral bony contact forces. Therefore, surgeons should consider tear propagation when deciding the most appropriate treatment option for small longitudinal tears of the lateral meniscus.

REFERENCES


